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DEVELOPMENT OF THERMOELECTRIC WATER HEATING/COOLING DEVICES

BY

B. MATHIPRAKASAM

MIDWEST RESEARCH INSTITUTE
425 VOLKER BOULEVARD
KANSAS CITY, MISSOURI 64110

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A simple, safe, and reliable thermoelectric device for heating or cooling potable water for use in military vehicles was developed. The unit is capable of cooling water to 60°F in ambient temperatures up to 130°F and heating to 150°F in ambient temperatures of 40°F. Freezing/overheating and undervoltage protections are provided. The unit has also cooling/heating indicators, water ready indicators, and automatic switch off. A total of six units were built, tested, and delivered to U.S. Army Natick R&D Center.

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PREFACE

This report describes the technical effort made by Midwest Research Institute (MRI) for the U.S. Army Natick Research and Development Center (NRDC) under Contract No. DAAK60-85-C-0011, Project Number 1L162724AH99, during the period February 1, 1985 to October 25, 1985.

The design work described in this report was performed by Dr. B. Mathiprakasam, the project leader at MRI. The experiments were conducted by Mr. Pat Heenan. Mr. Warren Roberts of Food Engineering Laboratory, NRDC* served as the project officer. The report was authored by Dr. B. Mathiprakasam, Principal Engineer.

The work was carried out in the Applied Sciences Section, headed by Mr. Doug Fiscus. The Applied Sciences Section is part of the Engineering and Materials Sciences Department at Midwest Research Institute.

*Recently renamed Food Engineering Directorate, U.S. Army Natick Research, Development and Engineering Center (NRDEC).

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I. INTRODUCTION

The U.S. Army has a need for a simple, safe, and reliable potable water heating/cooling device for use in their military vehicles. The Food Equipment Division of the Food Engineering Laboratory at the U.S. Army Natick Research and Development Center (NRDC) considered various options for designing such a unit and selected thermoelectric (TE) technology for this device. This is principally because the TE cooling/heating concept is considerably simpler, requires small size and weight, ensures safe and maintenance-free operation, and is extremely reliable compared with any other competing cooling/heating concepts.

NRDC built two engineering breadboard TE water heating/cooling devices with 10 oz water chambers. The first one, sized (6-1/2 x 5-1/2 x 8-1/2 in), employed a simple forced-convection assembly and single-stage TE modules, drawing 8 to 10 A at 24 V DC. The second one, sized (9-1/4 x 5-1/2 x 8-1/2 in), employed two such assemblies. This unit was capable of cooling 100°F water to 60°F in 5 min and heating 60°F water to 140°F in 3 min. The unit drew 15 to 18 A at 24 V DC. These units, while they have demonstrated that the concepts are practical, were not designed for optimum performance or engineered for operation in military vehicles. There was no built-in protection from freezing (in the cooling mode) or overheating (in the heating mode). Means provided for filling and drawing water were also not satisfactory. The units were not configured for mounting and use in military vehicles.

To design the TE units for optimum performance under severe operating conditions and also to equip the unit with various indicating, controlling, and protecting elements, NRDC contracted with Midwest Research Institute (MRI). This program required the development of six TE water cooling/heating devices. The essential requirements of these units are listed below.

The units must be capable of being filled by pouring from a standard canteen cup into the top of the unit. The units shall be rugged and corrosion resistant and capable of withstanding freeze-up. The tap or faucet shall be rugged, simple to operate, and capable of discharging into a standard canteen cup. The design should prevent inadvertent discharge of hot/cold water. The water chamber capacity shall be a minimum of 12.0 oz. The unit shall have provision for securing it to a horizontal or vertical surface. The design shall be such that it presents no hazards, such as burns or sharp edges, to the users.

The electrical system shall comply with Military Standard MIL-STD-454.[1] The design supply is 28 V DC and the unit shall not draw more than 18 A at this voltage. The switch(es) shall be designed to start a cooling or heating process and be installed to prevent inadvertent operation or damage. There shall be a protective circuit to terminate or prevent

the use of the device if the supply voltage drops to 23.5 V. There shall also be indicators when the unit is turned on and when the water is sufficiently heated or cooled. The unit shall be switched off automatically when the water reaches 40°F in the cooling mode and 170°F in the heating mode.

The desired thermal performances are: (1) cooling 12.0 oz of water to 60°F in 5 min starting at 100°F in a 100°F ambient and in 15 min starting at 140°F in a 140°F ambient; and (2) heating 12 oz of water to 150°F in 3.5 min starting at 60°F in a 60°F ambient and in 10 min starting at 40°F in a 40°F ambient.

Other general requirements included the design for high reliability and minimum maintenance, the size not exceeding 500 in^3, the ability to completely avoid spillage of water under the military vehicle operation across rough terrain, and the embossment of a serial number and contract number on each unit.

MRI has successfully completed the design and fabrication of six TE water heating/cooling units. The units were tested for their thermal performance, reliability, and maintainability. An analysis of the safety factors was also made.

This report provides the details of all technical activities carried out in this contract. The component and assembly drawings of the TE units, engineering, and associated lists are not included here but are being sent to NRDC separately. A System Safety Hazard Analysis Report was also prepared and is included in the Appendix.

II. DESIGN OF TE HEATING/COOLING DEVICES

An important element in the program of developing a TE heating/cooling device is the conceptual and hardware design of various components in the system so that the unit meets the essential requirements. The principal components in any TE water heating/cooling device are: (1) water chamber; (2) TE modules; (3) heat exchangers with fins to absorb heat from or reject to the ambient air; (4) fan to flow the ambient air through the fin assembly; and (5) electronic board to indicate and protect various processes and parts.

A. Water Chamber

Factors to be considered in the design of the water chamber are its capacity and ability to provide a high rate of free convection during heating and cooling. Since the TE modules are manufactured with flat surfaces, it is logical to choose a rectangular box to serve as the water chamber instead of cylindrical or any other shape. It is a usual practice to arrange a number of TE modules over one wall of the chamber and an equal number of modules on the opposite wall. The distance between these two walls is critical in the thermal performance of the unit. Theoretically,

this distance (we call it width of chamber) should be made as low as possible so that the temperature gradients across this distance are held minimum; this will enable the bulk water temperature to be close to the wall temperature. However, for a required volumetric capacity (for this program, minimum capacity required is 12 oz), the area of the walls where TE modules are attached increases considerably and exceeds the acceptable limits if the chamber width is highly reduced. The volume of 12 oz is equivalent to 21.6 in^3 and we decided to allow some excess capacity so that the chamber has a volume of 23.4 in^3. For this capacity, a width of 0.9 in translates to the wall area requirement of 26 in^2 and any width smaller than 0.9 in, was considered excessive penalty in terms of the wall area requirement.

The height of the chamber plays an important role in promoting the free convection inside the chamber and, therefore, it is desirable to keep the height more than breadth of the chamber. As can be seen later in the TE design description, each unit needed six TE modules on each wall and, therefore, a height of approximately 1.5 times the breadth is required to accommodate two columns by three rows of TE modules. This lead to a required height of 6.2 in and breadth of 4.2 in. With minor adjustments, the water chamber was designed to have 5.814-in height x 4.496-in breadth x 0.9-in width, all being inner dimensions. The adjusted inner volume is 23.515 in^3 (13 oz). In order to have a corrosive resistant and a good heat transfer characteristic surface, stainless steel was chosen to be the material for the water chamber. The plate thickness was 0.093 in. This brought the outer dimensions to 6.00 x 4.68 x 1.086 in.

B. Thermoelectric Modules

The design of TE modules required the development of computer models, the theoretical prediction of thermal performance, and then the optimization of various dimensions of the module. In the design of any TE device performing cooling and heating processes, it is usually more crucial to design the device for cooling than for heating. Normally, the TE module specifications are first determined based on the cooling requirements and are then checked as to whether they meet the heating requirements.

Under very severe ambient conditions, the difference between the ambient air temperature and water temperature at the end of cooling is as high as 80°F (140-60). A compact heat sink on the hot side will usually have about 30°F temperature differential to dissipate the heat. Also the cold side heat exchanger will need about 10°F temperature differential to absorb the heat from the water when it is at 40°F. Thus a total temperature difference (ΔT) of 80 + 30 + 10 = 120°F is expected between the hot and cold junction of the TE modules. This high ΔT suggests that we use a two-stage TE module for this unit.

A computer program was prepared to design the number and dimensions of the TE modules. This program was based on a transient-response heat transfer-thermoelectric model which assumes a force convection heat transfer on the ambient airflow side (which serves as heat rejection side in the cooling mode and as heat absorbing side in the heating mode) and

free convection heat transfer on the water side. During the initial phase of the program, it was assumed that the electronic components will have a negligible voltage drop and therefore a supply voltage of 28 V is totally available for the TE modules. With this assumption and also employing the correlation equations for free convection reported in the literature, the optimum number of TE modules, as determined from the results of computer program, was six on each side of the water chamber and each module will have the specifications as shown in Table 1.

TABLE 1

TE MODULE SPECIFICATIONS

	Stage 1	Stage 2
No. of TE couples	127	127
Height of elements	0.08 in	0.065 in
Cross section of elements	0.055 x 0.055 in	0.055 x 0.055 in
Voltage drop	7	7

The thermal performance of the unit as predicted by the computer program is shown in Fig. 1 for the cooling mode and in Fig. 2 for the heating mode. It can be seen from these figures that the chosen TE modules will meet the program's thermal performance requirements.

When the first unit was built and tested during the early part of the program, it was found that the complex electronic board consumed about 4 V, thus delivering only 24 V across the TE modules. As such, the actual thermal performance was much lower than the theoretical prediction (see more details on test data in the next chapter). Therefore, the computer program was run again to determine the new dimensions of the TE modules, assuming that they will be subject to a 24 V supply instead of 28 V. As per the new run, the element height changed to 0.065 in and 0.045 in, respectively, for Stages 1 and 2, while all other dimensions remained the same. The voltage drop across each module was 6 V. Five TE units built later in this program have TE modules with these new specifications. TE modules were purchased from MELCOR, Trenton, New Jersey, per MRI specifications.

C. Ambient Air Heat Exchangers

The heat exchangers used in the ambient airflow path serve to reject the heat to the ambient air in the cooling mode and to absorb the heat from the ambient air in the heating mode. The design of heat exchangers in the cooling mode is very critical since these are rejecting a large amount of heat. Theoretically, the heat rejection rate is the sum of heat removed from water being cooled and the heat equivalent of electric power supplied to the TE modules. Because of the volume constraints imposed

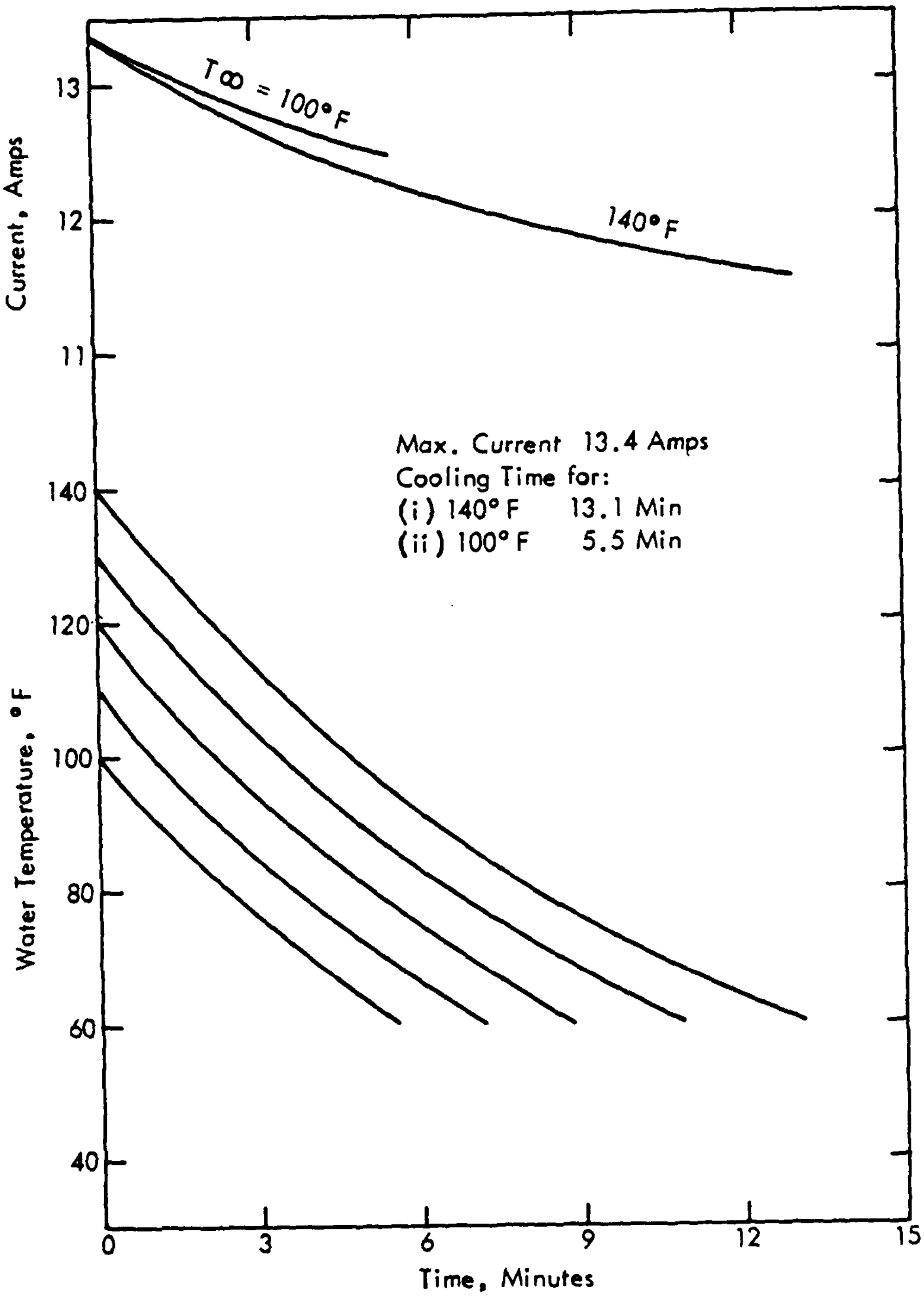

Figure 1. Theoretical performance in the cooling mode

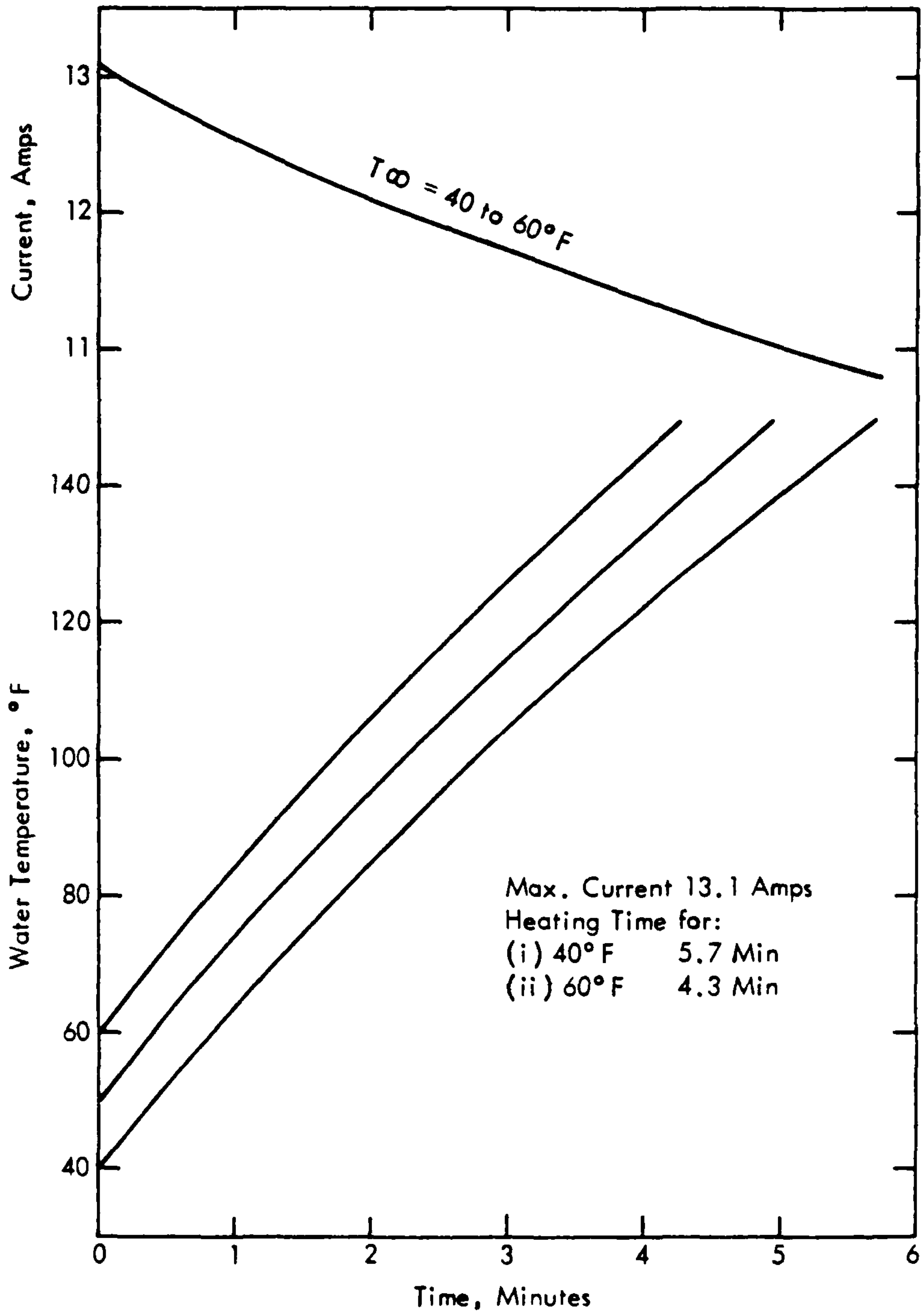

Figure 2. Theoretical performance in the heating mode

on the program, it was decided to choose a compact heat exchanger configuration. In the literature, a configuration commonly known as offset strip fin is considered very compact, having a large heat transfer rate per unit volume. The general arrangement of such a fin configuration is shown in Fig. 3.

In this geometry, the walls of the fluid passage are interrupted periodically along the flow direction. Each interruption breaks the hydrodynamic and thermal boundary layers, thus increasing the heat transfer rate. The data (both heat transfer and fluid friction) available in the literature for these fins are limited, and there are some correlation equations that can be used for design purposes.

Each fin in this geometry is made from a rectangular aluminum sheet 1.80 x 1.50 in by cutting four slots of size 1.25 x 0.20 in. There are 18 such fins in each base plate. In addition, there are also three short fins mounted in the central three slots. Short fins leave enough space in the base plate to accommodate fastening screws. Each base plate is a square 2.0 x 2.0 in and has 21 slots to accommodate the fins. There are a total of 12 heat transfer fin-base plate assemblies, with one for each TE module.

Design calculations showed that the average heat transfer coefficient attainable on these heat transfer surfaces will be on the order of 15 to 20 W/°F.

D. Fan

The fan required to move the ambient air over the heat transfer fins was selected to suit the flow rate-pressure drop relations described above from among several 28-V DC fans available in the market instead of trying to design one to suit the requirements. From among a number of DC mini fans available in the market, a fan manufactured by EG&G Rotron, Shokan, New York, Model No. PD24B2 was chosen as being appropriate for the TE units. This fan has a solid state brushless DC motor with polarity protection and 158°F maximum operating temperature. Its flow rate-pressure drop characteristic is given approximately by:

$$\text{cfm} = 260 - 165\ \Delta P - 150\ \Delta P^2 \quad (\Delta P < 0.3\ \text{in})$$

where ΔP is the pressure drop in inches of water. The nominal current flow is 1.0 A at 24 V. At 28 V, it may draw around 1.2 A.

E. Electrical System

The electrical/electronic board was designed to have several components in order to perform several functions such as: (1) provide power to the TE modules and fan in the cooling mode; (2) provide power to the fan, reverse the polarity, and power the TE modules in the heating mode; (3) switch on the appropriate indicating lights when the unit is on; (4) sense the water temperature and as soon as the temperature reaches 60°F (in the cooling mode)

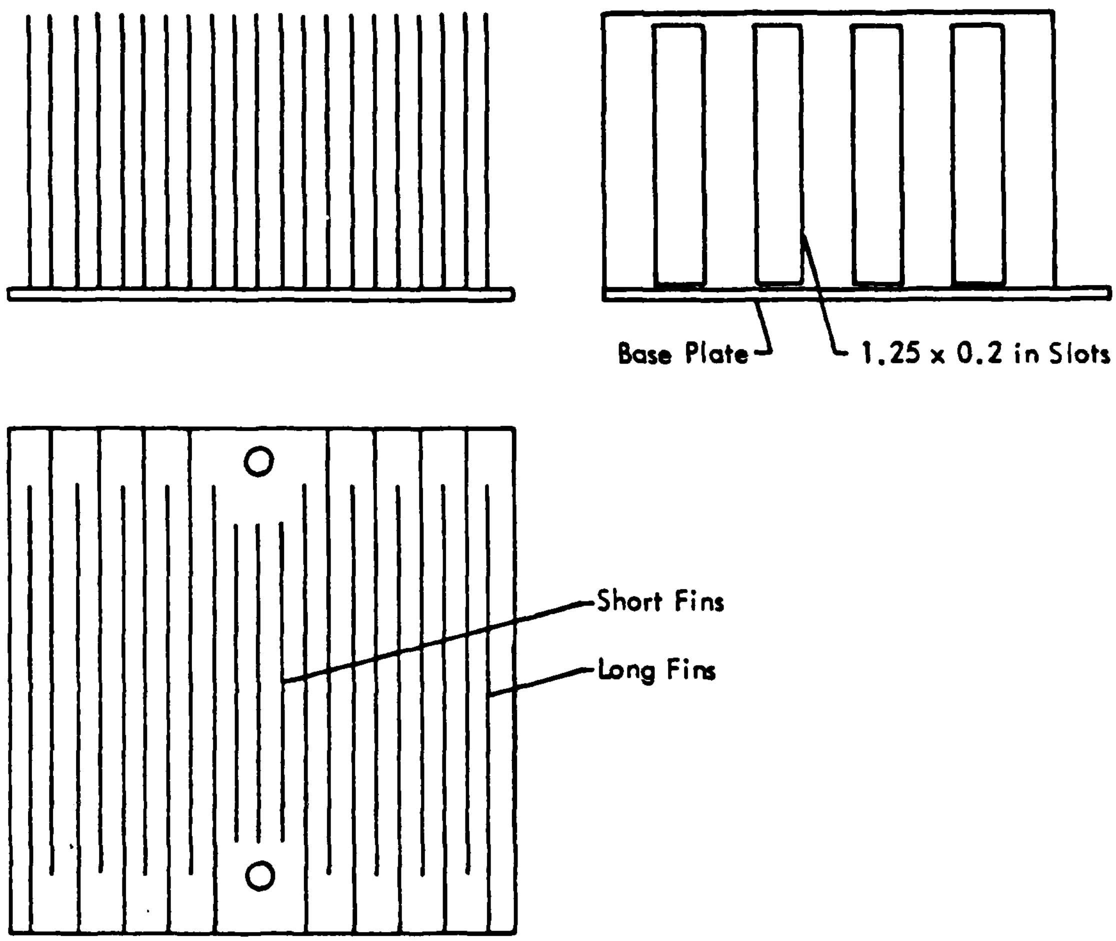

Figure 3. Ambient air heat exchanger configuration

or 150°F (in the heating mode), then switch on the appropriate ready lights; (5) continue cooling for 2 min, since the ready light is on if the mode of operation is cooling, or continue heating for 1 min since the ready light is on if the mode is heating; (6) switch off the power to the TE modules and fan at the end of 2 min or 1 min as described above (this protects the device from cooling below 40°F or heating above 170°F); and (7) keep the ready light on even after the power to the modules and fan is switched off until the water previously cooled below 60°F for-2 min warms naturally back to 60°F or the water previously heated above 150°F for 2 min cools naturally back to 150°F (at this point, the ready light goes off).

The base block diagram of the electronic/electrical board is shown in Fig. 4. This board provides control circuitry to switch power to the TE modules, the cooling fan, as well as the logic circuits used to monitor voltage levels and temperatures. When the power is first switched on, the voltage level is checked to see that it is above 23.5 V DC. If the voltage level is acceptable, then the rest of the logic circuit is enabled, and the user can operate the system. If the voltage level is less than 23.5 V, then the logic circuit is disabled and the user cannot operate the unit until the voltage level has been increased. As an added feature, the low voltage sensing circuit has a certain level of hysteresis built into it so that the operation of the unit will not be restored until the voltage exceeds 23.5 V by a fixed level. Because of this, the battery will not be fully discharged by the use of an auxiliary piece of equipment. The hysteresis assures that the battery charging system must be operating before restarting the operation by the logic circuit. The low voltage sensing level is user adjustable, and the hysteresis level is fixed so that a voltage in excess of 24 V (~ 25 to 26 V) would be required to start the system. The unit can be reset by switching the unit off then on again, but the same protective cycle will be active if the voltage drops below 23.5 V. The hysteresis also assures that the unit will not cycle off and on repeatedly, if it is near the 23.5 V threshold.

Once the system has been started at the proper voltage the user can then select either the heating mode or the cooling mode as desired. The mode is selected by processing the momentary contact rocker switch either down (for cooling) or up (for heating). The selection can be changed if desired after the cycle has finished or by switching the unit off and then back on again to reset the circuit logic. In this manner potentially damaging abuse of the TE modules by instantly switching heating/cooling modes is prevented. One of the two circuits is selected by the use of the rocker switch to provide the proper polarity to the TE modules and to select the appropriate temperature sensor. The use of two circuits allows independent adjustment of each temperature set point, custom design of circuit timing parameters, and the use of independent indicator lights to avoid user confusion. The circuit timer is actuated when the temperature set point has been sensed and the ready light comes on. This causes the logic to halt the operation of the unit within 2 min of achieving the set temperature for cooling (1 min for heating), thus limiting the overall temperatures to less than 170°F in the heating mode and greater than 40°F in the cooling mode.

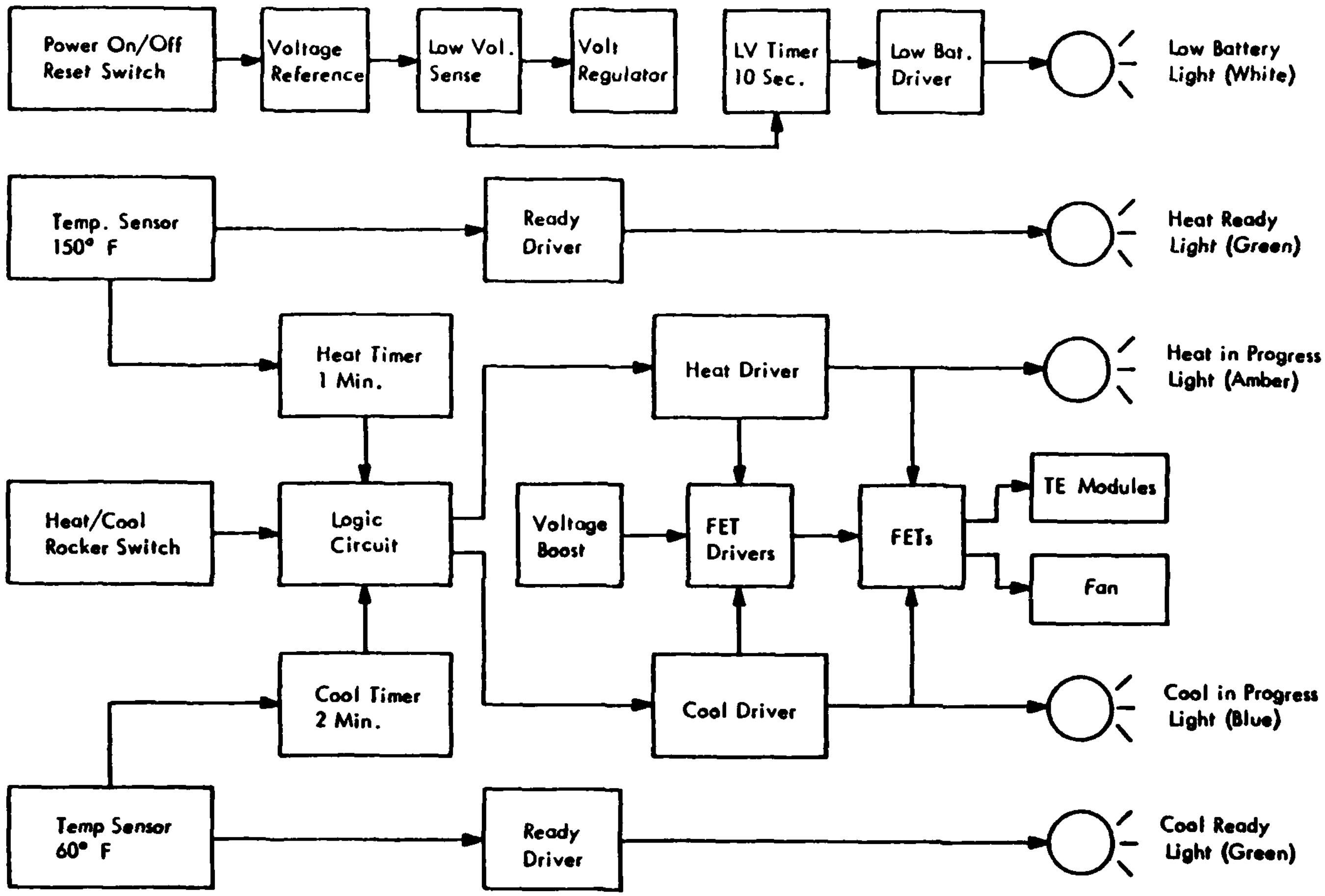

Figure 4. Electrical circuit diagram

Additional segments of the circuit provide support for the logic circuits. Two voltage regulator/reference circuits provide voltage levels substantially below the normal operating voltages to provide reference voltages immune to external voltage variations. Another circuit provides voltage boosts to the supply voltage for a driver circuit to activate the power Field Effect Transistors (FETs) used to switch the proper polarity power to the TE modules. The fan is controlled from an independent power FET to avoid polarity reversal to it.

The adjustable circuit parameters are the low battery reference voltage, a 10-V reference voltage and both of the temperature set points. They are currently set at 23.5 V, 10 V, 60°F (cool mode), and 150°F (heat mode). The indicator lights on the front panel consist of a group of two lights near the left top of the rocker switch and another two lights near the left bottom and one additional light below these near the bottom of the outer box. The lights near the top left of the switch reflect the operating status of the heating mode. The amber light indicates the heating cycle is active and the green light is the ready indicator when the proper temperature has been achieved. When first turned on and the heating cycle selected, the amber light will come on and stay on. Then, when the set temperature was sensed, the green ready light will come on, and the heating cycle timer will be started (both lights will now be on). At the end of the 1-min heating cycle, the timer will cause the logic to shut the power off to the modules, and at this time the amber light will go out and the green ready light will continue to stay on until the water temperature drops back to 150°F. A similar cycle occurs in the cooling mode with a blue light indicating an active cooling cycle and a green ready light. The white light near the bottom of the case indicates the low battery condition and will come on for a 10-sec period and cause the circuit logic to lock out the operation of the unit until the voltage is increased or the unit is reset by switching off then back on. Overcurrent protection is provided by a 15-Amp. resettable circuit breaker on the back of the unit near the power switch.

F. Outer Box

An outer box enclosing the water chamber, TE modules, heat exchange fins, and the electronic board supporting the minifan, and also carrying the various switches and indicators was designed. The box has an outer dimension of 9.47 x 7.43 x 6.5 in. The volume of the cooling unit is thus 457.4 in^3. In the outer box, there is one wall that is designed to be openable. This wall, which acts like a door to access the electronic board, is very convenient if adjustment and/or replacement of any electronic component is needed.

The general arrangement of various components in the cooling/heating unit is shown in Fig. 5, and a photographic view of the unit is presented in Fig. 6. One can see in this photographic view a spring-actuated cap at the top to add water and a spring-actuated tap near the bottom to discharge cold or hot water. Also installed in the outer box are an on/off switch, two indicating lights (one to show that the unit is in cooling mode and another to show the heating mode), and two ready lights (one for cooling and another heating), and also a low battery indicator.

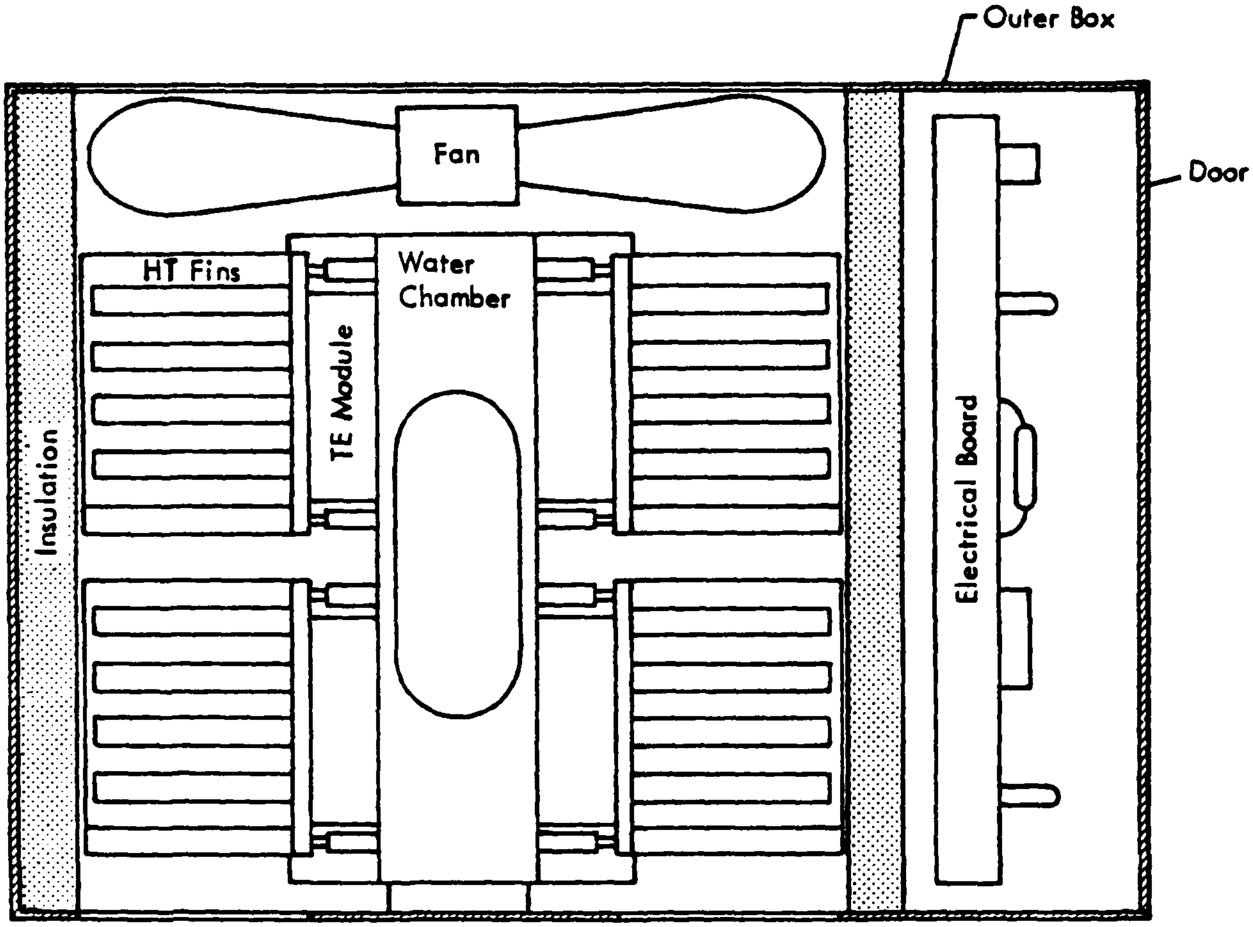

Figure 5. Arrangement of various components in the unit

(top view of interior)

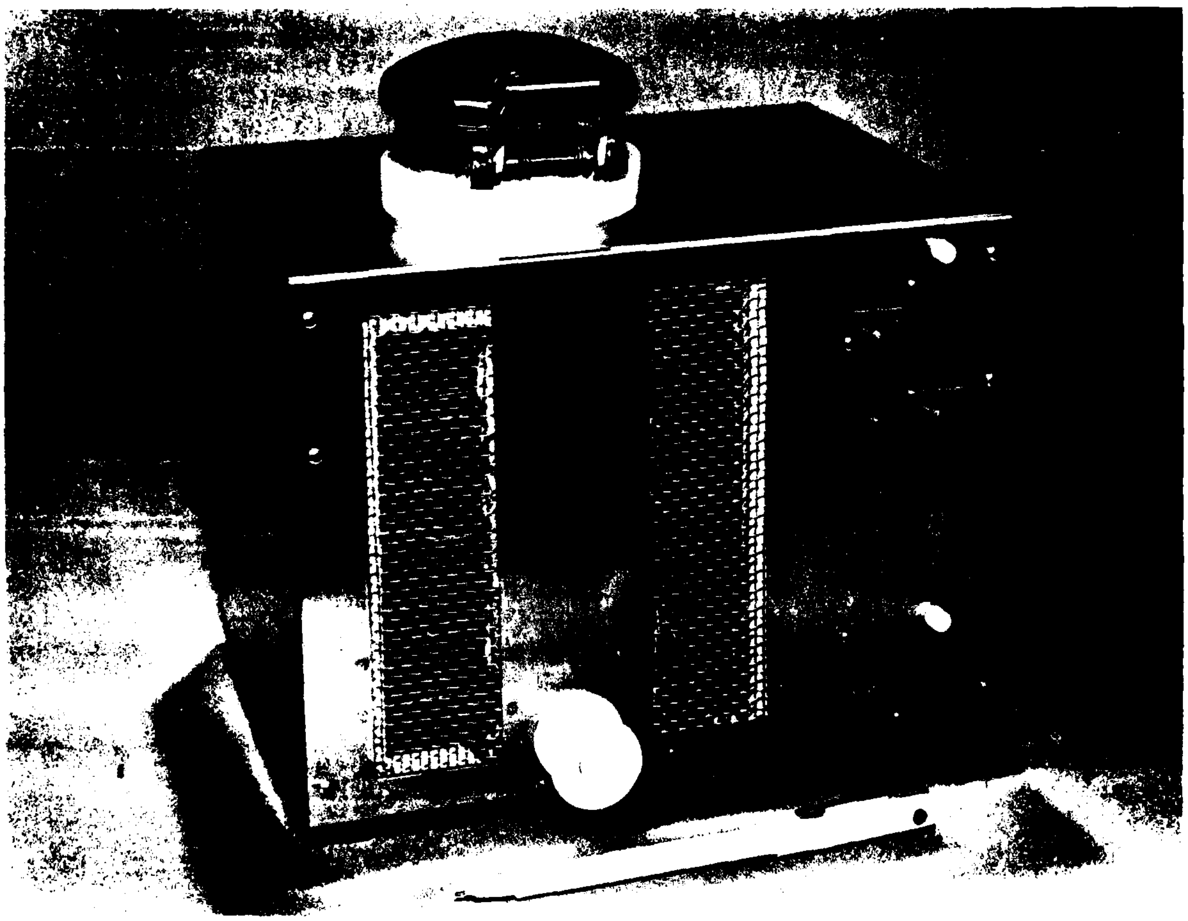

Figure 6. Photographic view of the TE unit

The preparation of necessary shop drawings as per the design specifications was made by EPIC manufacturing company, a local shop specialized in the manufacture of custom-designed units and components. This shop also fabricated the water chamber, heat exchanger fins, outer box and the electrical board, and finally assembled the unit.

III. PERFORMANCE EVALUATION AND DISCUSSION

The performance of the TE heating/cooling units was evaluated by conducting several electrical, thermal, and reliability tests. During the program one unit was designed and built first. Its electrical, thermal, and reliability data were collected before proceeding to the fabrication of the remaining five units. The information obtained from the first unit was used to modify some of the design details for building the other five units. This section presents the performance data of the first unit and also the other five units.

A. Electrical Performance

Several tests were conducted on all the units to verify the logic incorporated in the electrical circuitry. The normal operating procedure to cool/heat the water in the unit is as follows.

1. Check the main switch at the backwall to see if it is on. If not, switch this on. (This switch may be left on all the time.)

2. Add water in an amount not exceeding 12 oz by opening the lid at the top. Close the lid so that it locks.

3. Flip the heat/cool select switch to the desired position. The appropriate heat (amber) light or cool (blue) light will go on. (While cooling/heating is progressing, any action given to this select switch is ignored.)

4. Wait until heat ready/cool ready light (green) is on. Once the ready light is on, collect the water by pressing the tap knob.

5. If cooling/heating another cup of water is desired, then repeat Step 2, wait until both heat/cool and ready lights go off, and proceed with Steps 3 and 4.

Our performance tests show that the cycle proceeds without any problem both in cooling and in heating modes. The cycle cannot be interrupted by the select switch; however, the cycle can be interrupted anytime by turning the main switch off. As an example, if one has inadvertantly selected a heating mode instead of the intended mode of cooling, he could turn the main switch off, wait a few seconds, and turn it on to begin a new cycle. If one discharges the water before the cycle is complete, leaving the unit to continue the cycle, there will be no harm to the unit itself.

It will complete the cycle by merely cooling or heating the water chamber walls. These inadvertant processes were tried intentionally to confirm the safe operation of the unit.

The unit was also tested for its activation of the low voltage circuit cutoff. When the supply voltage was set to 23.5 V, or during a cycle when the supply voltage was reduced to 23.5 V, the cycle was terminating, illuminating the low voltage indicator. The unit was also tested for any electrical leakage in heating and cooling cycles and found to be free from such leakages. In general, the electrical performance of the unit appears to be very good.

B. Thermal Performance

The units were also tested to verify their thermal performance. As mentioned above, one TE unit was first built and tested before proceeding to the design and fabrication of remaining five units.

We observed in the first unit that the mounting of the thermal sensor used to trigger the ready light on when the water is cooled to 60°F or heated to 150°F was not proper in terms of ample heat flow into its sensing elements. In the cooling mode, this resulted in a spread in temperatures at which the ready light was triggered, depending upon the initial temperature. While setting the unit, the water was cooled from room temperature (~ 75°F) and adjustments were made to trigger the ready light when the bulk water temperature (measured after discharging it in an insulated container) reached 60°F. With that setting, when the unit was tested with an initial water temperature of 100°F in a 100°F ambient, the ready light did not indicate 'on' until the water reached 51.5°F. At 110° and 120°F, the corresponding ready light on temperature was 48.0° and 42.0°F, respectively. In 130°F tests, the ready light never lit, thus showing its triggering temperature is below the absolute minimum temperature the water can attain. To minimize the problem of this temperature spread, the mounting process was modified in the next five units. (In the heating mode, this spread was less than 5°F, an acceptable value.)

The time required to cool the water to 60°F or heat it to 150°F was also determined through the laboratory tests. Table 2 shows the performance of the first unit. In general, the performance of the first unit was not up to the expectation.

Since the performance of the first unit was below the theoretical predictions, an attempt was made to determine the cause. It was first noticed that the voltage drop across the electrical board is nearly 4 V thus allowing only 24 V to the TE modules. Since the modules were designed to operate at 28 V, it was thought that it was the relatively low and non-optimum supply voltage that produced the less-than-expected performance. Subsequently, the TE modules were redesigned so that their optimum operating voltage is around 24 V. The five units built later in the program were provided with these newly designed TE modules.

TABLE 2

THERMAL PERFORMANCE OF THE FIRST UNIT

Process	Ambient Air Temperature, °F	Water Initial Temperature, °F	Time in Minutes to Attain 60°F	Time in Minutes to Attain 150°F
Cooling	100	100	6.4	-
Cooling	110	110	10.0	-
Cooling	120	120	15.0	-
Cooling	130	130	19.2	-
Heating	60	60	-	5.8
Heating	45	45	-	7.7

After building the five new units, thermal performance tests were repeated on all of them. First of all, we measured the temperature spread and found it to be within 7°F in the cooling mode and within 3°F in the heating mode. This is a significant improvement. With 75°F initial water temperature (at 75°F ambient), the ready light 'on' was set at 62°F and with the same setting, the ready light was triggered at 55°F with an initial temperature of 130°F (at 130°F ambient). For initial temperatures greater than 75°F but less than 130°F, the ready temperature was between 62° and 55°F.

The time required to cool the water to 60°F or heat it to 150°F was reduced in the five units compared to the first unit, but the reduction was not to the satisfactory extent. This happened in spite of the fact that the TE modules were redesigned for 24 V instead of 28 V. The new values were 6.3, 9.6, 13.3, and 18.5 min for the initial water temperatures of 100°, 110°, 120°, and 130°F, respectively, in the cooling mode (compare these values with those given in Table 2). In the heating mode, 5.5 and 7.0 min were required with the initial temperatures of 60° and 45°F, respectively.

Since the supply voltage, as measured in the new units, across the TE modules was around 24 V and, therefore, closer to the design voltage, we believe that the less-than-expected thermal performance is not due to the design of the TE modules. A possible cause now appearing to be a major factor may be the existence of a very low natural convection heat transfer within the water chamber, especially at low water temperature. The value of a parameter, normally written as $(g\beta\rho^2/\mu^2)$, which indicates the order of magnitude of natural convection heat transfer is 118 x 10^6°F^{-1}ft^{-3} for water at 100°F and it reduces to 8 x 10^6°F^{-1}ft^{-3} at 50°F (a reduction by a factor of 14.75). A very low natural convection heat transfer on the water side (especially in the cooling mode) may offer an excessively high thermal resistance for the heat flow, thus reducing the thermal performance.

C. Reliability Tests

TE units were also tested for their operational reliability. The units were cycled several times (~ 20 times in cooling and ~ 20 times in heating mode). No problem was encountered in these tests. Therefore, it is concluded that the units should be highly reliable for operation involving several hundred cycles of cooling, heating, or their combination.

IV. CONCLUSIONS AND RECOMMENDATIONS

The design, fabrication, and testing of a simple, safe, and reliable potable water heating/cooling device was undertaken and completed successfully. A total of six units were built in the program. The first unit was built based on the initial design and a few minor modifications were made in the next five units. The units have all the required protection/indicating/controlling elements. Satisfactory means have been provided for filling and discharging water from the units. The electrical and reliability test results meet the program requirements. The thermal performance, however, is slightly less than expected. The probable cause for this was also identified in the program.

The program of heating/cooling unit development was indeed interesting and challenging. The experience gained in various tasks of this program suggests that a number of possible improvements should be looked into in a future research program. The following recommendations are made to U.S. Army, identifying some of the key areas for improvement.

1. The principal mode of heat transfer within the water chamber is natural convection. In order to improve the thermal performance, it appears necessary that some form of heat transfer augmentation be incorporated. Such an augmentation may vary from providing internal fins of various configurations to disturbing the thermal boundary layers by employing some kind of stirrers (mechanical or magnetic). Investigation in these lines was outside of the scope of the current program; therefore, a program should be initiated to enhance the heat transfer aspects in the water chamber.

2. The internal surface of the water chamber is an untreated stainless steel surface. Since the water to be cooled/heated is potable, the surface needs to be covered with a thin coating of glass or other material. Such a coating may be necessary for the unit to have it approved by FDA before being commercially made.

3. While we observed no major drawback of the use of a heat exchanger fin-fan combination to reject/absorb heat from the ambient air, no other fin configuration with a matching fan was tried. Improvements in this component are also possible. It is even worth investigating fuel-circulated (instead of air circulated) TE devices in which heat is absorbed from or rejected to the vehicle fuel tank by circulating the necessary amount of fuel from the tank. This concept does not consume fuel but uses the fuel as a huge reservoir of heat/cold. The cooling period can be significantly reduced in this concept, since the bulk fuel will be at a temperature much lower than ambient air temperature at any time and its heat transfer characteristics are also vastly superior to that of air.

LIST OF REFERENCES

1. Military Standard MIL-STD-454, General Requirements for Electrical Equipment, 1984.

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APPENDIX

SYSTEM SAFETY HAZARD ANALYSIS REPORT

SYSTEM SAFETY HAZARD ANALYSIS REPORT

I. Introduction

The U.S. Army Natick R&D Center (NRDC) has a requirement to design and fabricate a simple, safe, and reliable thermoelectric (TE) water cooler/heater. In response to this requirement, Midwest Research Institute (MRI) submitted a proposal to perform the design and fabrication tasks. Subsequently, NRDC awarded a contract to build six TE water heating/cooling units. The activities of the program were completed by MRI recently.

One of the reporting requirements of this contract is the System Safety Hazard Analysis Report to be submitted to the contracting officer. This report documents the subsystem hazard analysis (SSHA) performed to identify hazards associated with design of subsystems including component failure modes, critical human error inputs, and hazards resulting from functional relationships between components and equipments comprising each subsystem.

II. Scope of the Overall Program and the Related Safety Program

The scope of the overall program is to design and fabricate a simple, safe, and reliable thermoelectric unit for use in military vehicles to cool or heat potable water. Six units will be built and delivered to the U.S. Army. The safety aspects of the program include designing the units without sharp edges, hot spots, etc.; building the unit without any electrical hazards; and providing the unit with necessary indicators to alert the users for necessary action.

III. Safety Program Organization and Management

The safety aspects of the program was principally managed at Midwest Research Institute by Dr. B. Mathiprakasam, project leader of the overall program. He was assisted by Mr. Pat Heenan and also by a safety committee organized by the Engineering and Materials Sciences Department in which the program was undertaken.

IV. Safety Program Milestones

The evaluation of the effectiveness of the System Safety effort was undertaken along with the evaluation of the technical performance of the cooling unit. The building of the first unit was completed by June 30, 1985. Therefore, the safety aspects incorporated in that unit was evaluated during the first week of July 1985. The building of the remaining five (5) units was completed by September 30,1985. In these units the safety aspects were inspected during October '985.

V. Safety Requirements

The following is a list of engineering requirements and design criteria for safety.

1. All the components exposed to the user were designed without sharp edges.

2. The hot spots in the unit were well insulated and/or covered so that they cannot be reached by the user inadvertently.

3. Electrical/electronic controls have been provided in order to protect heating of the water above 170°F or cooling it below 40°F. Overheating of the TE modules was also protected because of this.

VI. Subsystem Hazard Analysis

The subsystem hazard analysis showed that there are no serious hazards associated with the cooling unit. From the human error point of view, it may be possible that the crew member who intended to cool the water inadvertently could switch the unit to the heating mode. The possible hazard in this process is that in order to collect the water, he may hold a cup thinking that it is cold but he is subjected to a 150°F temperature contact. Another safety feature built into the electrical board is the incorporation of hysteresis in the low voltage protection circuit. The benefits of this safety feature will diminish if the line losses are large. Therefore, it is advisable to keep the lengths of lead wires to a minimum in order to reduce the voltage drop in these lines and to realize the benefits of hysteresis. The line losses will also shift the cutoff voltage from 23.5 V by an equal amount.

No hazard was encountered during the entire phase of testing the TE units.